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DESIGNING A CONSTRUCTION SUPPLY CHAIN MODEL USING BACKUP SUPPLIER AIMING AT OPTIMIZING RESILIENCY AGAINST DISRUPTION

Mahsa BADKOUBEH, Seyed Farid GHANNADPOUR✉

School of Industrial Engineering, Iran University of Science & Technology, Tehran, Iran

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Abstract. Resilience is a topic that has recently emerged concerning the basics of the construction project supply chain and we can consider it as a response to disruption in the supply chain of the project. Disruption also is an unavoidable reality in today's complex and dynamic construction supply chain, the occurrence of which can cause irretrievable damages to the system, such as financial losses. Successful companies seek to minimize disruption and maintain adequate supply chain performance before disruption occurs, rather than looking for costly and challenging post-disruption solutions. This paper covers this gap by proposing a scenario-based mixed integer-programming model aiming to minimize logistics costs and delays, while scheduling projects to address selecting the appropriate supplier at risk of disruption. So far, this quantitative view was not presented in discussions about disruptions in the project supply chain, therefore different scenarios are applied in the process to validate the model. To improve its resilience level, this model benefits from back-up suppliers' strategy. This study focuses on providing the required materials for the project site in an emergency without incurring additional costs using a back-up supplier. Results reveal the model's suitability in confronting the unavailability of a supplier due to disruption.

Keywords: multi-projects supply chain, project scheduling, primary supplier selection, back-up supplier selection, disruption, resilience, construction project.

✉Corresponding author. E-mail: *ghannadpour@iust.ac.ir*

1. Introduction

Despite the increasing number of researches on supply chains, there is a gap of extensive review on their disruptions and solutions. In recent years, it has been receiving increased attention in line with which, in this paper, authors study a supply chain problem involving disruption and back-up suppliers seeking to maximize the supply chain efficacy. Each construction project team is required to complete their projects in due course. One of the obstacles to achieving this goal is lack of timely provision of resources (Kerzner, 2002). Many reasons can result in a lack of timely supply of resources, one of which is the occurrence of disruption in suppliers. Generally speaking, supply chain risks can be divided into two categories: operational risk and disruption (Tang, 2006). Operational risks point to inherent uncertainties that inevitably exist in supply chains. These inherent uncertainties include but are not limited to, lack of customer demand and cost uncertainty. In addition, this uncertainty caused by operational problems such as equipment failure, power outages, and the absence of crucial labor. Disruption risks in a supply chain are the major disruptions naturally caused; they also include technological threats such as terrorist attacks, employee strikes, floods or earthquakes. On the other hand, operational risks with moderate to high probability of occurrence have only short-term negative effects. While disruptions with low probability of occurrence cause destructive incidents with high negative effects, which may even have long-term negative effects. However, today's global supply chains are more prone to unforeseen and humane natural disasters such as floods, volcanic eruptions, earthquakes, tsunamis, fires, transportation accidents, and labor strikes (Torabi et al., 2015). The Boeing Dreamliner program, for example, lost about $ 2.5 billion cash flow because of bolts and nuts shortage arising from a malfunction in one of its smallest suppliers (Greising & Johnsson, 2007). After Japan's earthquake in 2011, Apple suffered from a shortage of critical components for the iPad 2, including its super-thin battery and flash drive manufactured exclusively by Apple Japan (Torabi et al., 2015). The Icelandic Volcano in 2010 and the earthquake in Japan in 2011 disrupted universal supply chains, including the car sector and retail SC in the UK (Massey, 2011). After 2011 Japan earthquake, Nissan car manufacturers suffered severely due to its reliance on a factory in the quake-hit area that supplied 12 percent of its engines (Torabi et al., 2015). This earthquake forced Nissan manufacturers in England's Sunderland to close the factory for three days because of the shortage of parts from Japan (Massey, 2011). Recently, also the sandstorm has caused huge disruption in supply chains of US (Burnson, 2012). Owing to the temporary nature of the project supply chain, the impact number of stakeholders on the project supply chain, and the necessity for maximum flexibility and agility in the existing flows in the project supply chain, paying attention to this type of disruption that causes the project supply chain to fail and would result in financial losses, gains more importance. These events show that supply chain disruptions are sometimes a severe threat to the continuation of the ordinary course of projects. As a result, supply chain resilience has recently become a primary concern for large corporations. A recent report by the World Economic Forum indicates that supply chain disruptions reduce the shares of affected companies by an average of 7% (Garcia-Herreros et al., 2014).

In this article, considering the importance of construction projects and the probability of occurrence of some accidents some decisions made: while choosing the appropriate suppliers for the timely supply of the materials required for each project, improving the supply chain of the project addressed using the strategy of back-up suppliers.In this process, different disruption scenarios taken into account. In general, the questions answered at the end of this research summarized as follows:

- What model can be used to minimize the cost of scheduling multi-project supply chain activities in the event that an alternative supplier has to be selected due to disruptions?
- How does the model react under various scenarios of disruptions?
- How can the model be practically applied to construction supply chains?

Given the concerns about disruption, in this study, we present a mixed integer scheduling to select suitable suppliers along with project scheduling, intending to reduce logistical costs (purchasing, ordering, shipping, and delay) and scenario-based costs, together with the back-up supplier strategy, to make the project supply chain model resilient.

This article is the first study in the literature of the subject that performs suppliers' selection in a project supply chain along with scheduling the activities of each project under a variety of disruption scenarios targeting at resilience of a construction supply chain.

Figure 1 completely categorizes the most frequently used keywords by authors in this area and the data are on the coordinate axes. One axis represents the density and the other axis shows the centrality of the subject. In our subject area, it can state that the issue of disruption and supply chain are central, that is, they are important issues, but in few researches, these issues considered. Our article is a very new and practical work in this field.

The rest of the article prepared as follows. Section 2 provides an overview of related literature in which we will have a short discussion about previous related works. The problem statement and the proposed model along with the analysis of various case studies presented in Sections 3 and 4, respectively. Finally, Sections 5 and 6 are about the discussion, conclusions of this study and the results stated with the authors' recommendations for further researches.

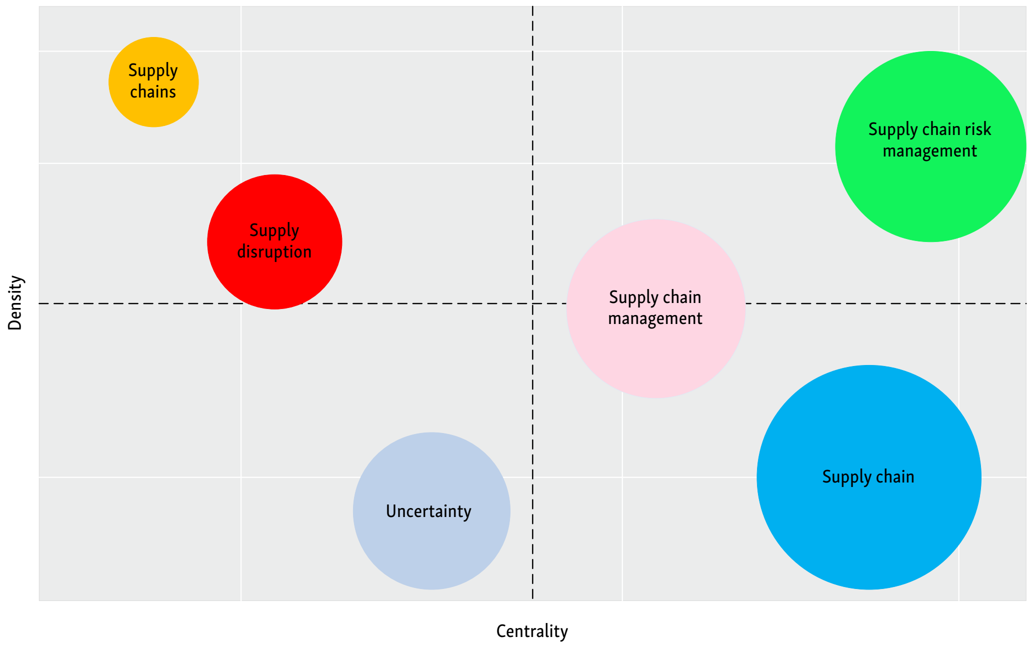

Figure 1. Frequent key issues of the supply chain

2. Literature review

The literature review section goes through previous studies on the construction project supply chain, the construction project supply chain with disruption, and finally the resilient construction project supply chain.

2.1. Construction project supply chain

Korpysa et al. (2020) clarified that project supply chain is mainly rooted in the need to increase the value of its members. In addition, this article also described the most important concepts of the project supply chain and presented a performance plan. RezaHoseini et al. (2021) evaluated the construction project supply chain using a mathematical model that considered project's time constraints in addition to the actual environmental effects of the vehicles. They did this in such a way that in addition to minimizing logistics costs, including purchasing, ordering, and shipping costs, the pollution and greenhouse gas emissions also minimized. Moreover, projects are subject to final quality inspections by the Joint Committee, requiring ongoing project review. Finally, the results of the mathematical model analyzed using Fuzzy and Probabilistic Theory. For further information on the subject, researchers can refer to the following studies: Behera et al. (2015), Stamatiou et al. (2019), Cheng et al. (2010).

2.2. Construction project supply chain with disruption

Craighead et al. (2007) focused on two issues: how and why a supply chain disruption could be more severe than another. They employed a multiple-method, multiple-source empirical research design and derived six propositions relating to disruptions severity in supply chain. The research results augmented knowledge of supply chain risk, resilience, vulnerability, and business continuity planning. Authors investigated long-term stock price and equity risk effects of supply chain disruptions. They examined stock price effects from one year before through two years after the disruption announcement date. Most of the underperformances were observed in the year before the announcement, the day of the announcement, and the year after the announcement. Moreover, they found evidences indicating that firms did not recover quickly from harmful effects of disruptions, and around the announcement date, firms' equity risk increases a lot. Qi et al. (2004), in their paper, presented a one-supplier–one-retailer supply chain experiencing a disruption in demand during the planning horizon. They showed that changes to the original plan induced by a disruption can impose high deviation costs throughout the system. One of their general goals was to analyze these kinds of costs, and they used wholesale quantity discount policies. They also derived conditions under which the supply chain can coordinate in order to realize the maximum potential profit. Kumar and Sharma (2021) in their paper concerned business-to-business firms, and the extraordinary interruptions of the pandemic that caused unprecedented shocks to global supply chains. They applied chaos theory by employing a single-case method, to find out the disruptions that happen to the business-to-business oil and gas supply chain. Their findings indicate significant implications for educators concerning supply chain disruptions, especially in crises. Senouci and Mubarak (2016) presented a multi-objective optimization model to schedule construction projects under extreme weather conditions. Two tangible samples of the extreme weather influences on construction time and cost provided. The first one showed the influence of extreme weather on construction time and cost. The second one demonstrated the model's ability for generating, and visually presenting the optimal trade-offs between duration and costs of construction projects under extreme weather conditions.

Kaur and Singh (2022) in their article "Disaster resilient proactive and reactive procurement models for humanitarian supply chain", stated their concern about global and complex supply chains which have always been exposed to the disruptions caused by disasters around the world. The researchers believe that as a result of this issue many business firms face challenges for designing resilient supply chains to minimize the disruptions effect specially those caused by natural disasters. They selected procurement as one of the primary supply chain activities that make us sure about undisrupted supply of raw material. They proposed a framework of disaster resilient procurement involving process of resilient supplier selection as a proactive view to disaster resilient supply chain. For disaster resilient procurement, the authors applied two mathematical models: 1) Proactive situation in which the model allocates the orders to suppliers that are resilient to disaster; 2) Reactive model that in disruptions reallocate orders for minimizing penalties incurred by shortages. Their framework purpose is achieving operational excellence by minimizing costs and risk of disruptions simultaneously. In a paper under title of "Disruption-resilient supply chain entities with decentralized robust-stochastic capacity planning", Tafakkori et al. (2023), presented models for four types of supply chain entities. These decentralized capacity planning models developed based on metrics such as functional similarities, and novel resilience for maximizing cost-efficiency and resilience at the same time to select proper business continuity plans. At the end they tailored a method of robust-stochastic optimization for addressing the uncertainties related to available time of recovery and disruptions occurrence and impact. They simulated disruption scenarios using a discrete-time Markov chain. The results demonstrated important features of business continuity plans, offered optimal decisions for enhancing resilience, and predicting about disruptions or proactive/reactive planning.

2.3. Resilient construction project supply chain

The objective of Hu and Du (2010) research was how to design an appropriate operation model for reducing uncertainty. They said that the supply chain can be divided into two models: static chain and net model. According to this assumption, their paper studied series and parallel systems and analyzed the model reliability in detail. They argued that improving reliability depends on the reliability of subsystems or components rather than increasing the number of subsystems or components. Garcia-Herreros' et al. (2014) objective was minimizing the sum of investment cost and expected distribution cost during a finite time horizon. The method they used contained an "strengthened multi-cut Benders' decomposition algorithm and the derivation of deterministic bounds based on the optimal solution over reduced sets of scenarios". Results demonstrated the importance of including DC capacity in the design problem and anticipating the distribution strategy in adverse scenarios. Cardoso et al. (2015) applied a design and planning model that integrated demand uncertainty for five supply chain structures submitted to disruptions' different types. For assessing the supply chains' resilience (comprising network design), centralization, and operational indicators, they considered eleven indicators. For illustrating the methodology, they used a case study of a European supply chain. As per them, "a discussion on the results obtained is presented in order to conclude which main characteristics, a manager should consider when designing and planning resilient supply chains". Jabbarzadeh et al. (2016) presented a hybrid robust-stochastic optimization model in their paper plus a Lagrangian relaxation solution method to design a supply chain. They designed this supply chain resilient to 1) interruptions of supply/demand and 2) disruptions of facility whose occurrence risk and impact magnitude could be mitigated by fortification investments. The probability of disruption occurrence in their paper is expressed as a function of facility fortification investment to hedge against potential disruptions when certain budgetary constraints are present. The authors also used a Monte Carlo simulation method to examine the performance of the proposed model. They discussed a real-world case example in their paper that addressed mitigating facility fire risk in an actual oil production company for exploring the practical application of the proposed model and methodology. Researchers focused, in their analysis and investigation, on exploring the extent to which design decisions of supply chain were under influence of factors such as facility fortification strategies, conservatism degree of a decision maker, demand fluctuations, variations of supply capacity, and budgetary constraints.

Snyder et al. (2016) also had a literature review about OR/MS regarding supply chain disruptions to take research stock to date and to provide a research questions overview that addressed. To do this, they first placed these disruptions in the context of supply uncertainty and discussed common modeling approaches. Then they discussed about 180 scholarly works on the same topic, which organized in six categories: 1) evaluating supply disruptions; 2) strategic decisions; 3) sourcing decisions; 4) contracts and incentives; 5) inventory; and 6) facility location. In the end, they concluded with discussing future research directions for other eager researchers. Schmitt and Singh (2012) analyzed the back-up methodologies, and inventory placement in a multi-echelon network, and examined their effect on reducing supply chain risk. They developed a simulation model for capturing an actual network, and used a consumer-packaged goods company for analysis. The authors presented insights and analysis for multi-echelon networks, and showed how network utilization and proactive planning cause reductions in supply chain's disruption impact. The effectiveness of incorporating three types of redundancy practices (pre-positioning inventory, back-up suppliers, and protected suppliers) into a firm's supply chain was assessed fully by Kamalahmadi and Parast (2017). They developed a two-stage mixed-integer programming (two-stage MIP) model as a General Model using the concept of a decision tree to capture different disruption scenarios. Finally, findings suggested that comparing to the General Model, all three strategies reduce risks and costs. They analyzed risks, costs, reliability, and dependence on each strategy. They analyzed those factors to provide insights into supplier selection, demand allocation, and capability development in a supply chain under risks. Torabi et al. (2015), in their research, investigated supplier selection and order allocation problem for building resilient supply base, under operational and disruption risks. Their model accounted for critical data epistemic uncertainty and applied several proactive strategies. They designed a five-step method for solving the problem efficiently. The computational results showed the significant influence of considering disruptive events on the selected supply base. According to Palliyaguru et al. (2012), there is a need for research to identify the most beneficial disaster risk reduction (DRR) strategies that effectively cause reduction of vulnerability. The authors took the case study approach, and their paper based entirely on data collected from semi-structured interviews and a questionnaire survey that conducted in one case study in Sri Lanka and expert interviews that conducted in Sri Lanka and the United Kingdom. Finally, they concluded "however, none of the emergency preparedness strategies are satisfactorily implemented, most of the physical/technical strategies implemented adequately".

"Building construction supply chain resilience under supply and demand uncertainties" is the article written by Chen et al. (2024), presenting a construction supply chain model which is both multi-period and multi-product. It emphasizes the importance of back-up supplier by showing capacity and material demand uncertainties. The researchers adopted the robust optimization for addressing model uncertainties. They focused on back-up sourcing issues and backordering decisions and the answers were informative for general contractors and provided valuable insights for enhancing construction supply chains' resilience. Their findings showed that "back-up supplier idea is sensitive to its' unit transportation fees" and unit material price. Furthermore, back-up supplier issues initially deal with the supply-side risk. Ribeiro and Barbosa-Póvoa (2023) stated that "Supply Chain Management is in constant evolution, and Supply Chain Resilience (SCR) appears as a recent offspring result of changes in how companies do business". Their work "A responsiveness metric for the design and planning of resilient supply chains" have led to concentration on the basic concepts of supply chain resilience as they noticed a research gap on the modelling and quantification of the supply chain resilience behavior. The authors' researches demonstrated that supply chain resilience models majorly failed to incorporate relevant characteristics of the SC performance and tried to addresses such gaps to propose a new resilient SC metric. They applied the model to a case study showing that adopting universal strategies should be avoided and defining the best plan for SC operation should be replaced. The analyses clearly led to a correlation between the Supply Chain performance and the new Supply Chain Resilience metric which makes the process of designing and planning the Supply Chain easier. "The interaction of sustainability and resilience has not been sufficiently addressed in the supply chain literature", according to Mehrjerdi and Shafiee (2021). They explained that "applying sustainability and resilience concepts into a supply chain means the simultaneous optimization of the cost and recourses, including human and environmental ones, for facing possible risks". Thus, the primary motivation of their paper "A Resilient and sustainable closed-loop supply chain using multiple sourcing and information sharing strategies" was considering resilience and sustainability in a supply chain at the same time. For this purpose, they used questionnaires to identify the supply chain's strategies impacts on the resilience. They used fuzzy TOPSIS to solve the resulting matrix while the information sharing selected as the first and multiple sourcing chosen as the second strategy. The research results demonstrated the necessity of mixing resilience and sustainability in the supply chain. Aldrighetti et al. (2023) delivered their message via an article under title of "Efficient resilience portfolio design in the supply chain with consideration of preparedness and recovery investments". According to the authors, supply chain resilience is forced to cope with disruptions and abilities of recovery such as backup suppliers. In this study, they engaged in answering "how to add resilience components into supply chain network design so that it incurs the minimum costs at the preparedness stage and allows for efficient and effective recovery in case of a real disruption?". To answer this question, the paper presented a model to design a useful resilience portfolio in a multi-echelon supply chain. In a real-life case-study applying comparative and computational analyses, they showed that the model determines a combination of recovery and preparedness investments. They illustrated their approach that allows identification of very important relationships between disruption duration and recovery strategies like back-up supplier. For further information on resilience, authors suggest referring to Sawik (2022), Shen and Ying (2022), Kamalahmadi et al. (2022), He et al. (2022), Ergun et al. (2023), Aghajani et al. (2023) and Shishodia et al. (2022). A selection of essays been discussed in Table 1.

2.4. Research gap and contribution

Considering the importance of the issues mentioned above, the contributions of this article are as follows:

- Presenting a comprehensive model for selecting suppliers in construction projects and planning multi-project activities in the event of a disruption.
- Considering the dependence of suppliers' available capacity on each other during a disruption.
- Assigning standard and back-up capacities to suppliers according to different disruption scenarios.
- Determining amount of shortage in each scenario, and considering purchase costs, ordering, shipping and delay in the mathematical model.

3. Multi-project planning and scheduling model considering disruption and back-up supplier strategy

3.1. The problem statement

The construction industry has complexities that distinguish it from other industries (Fearne & Fowler, 2006). Sometimes, due to the complexities of the construction supply chain, it becomes challenging to remove the obstacles that prevent it from improving its performance. One of these obstacles is the occurrence of unjustifiable disruptions such as natural disasters, strikes, accidents, and terrorism. In this study, we investigated the occurrence of disturbances that cause problems in suppliers' service providing. In the general model, a set of discrete scenarios $SC = \{1, \ldots, sc\}$, each with the definite and same probability of occurrence π_{sc}, is defined for different types of events that may occur as a result of the disruptions. In addition, the parameter $SI_{sc.s}$ defined as the state of disruption in supplier s in the sc scenario. In this study, the capacity of set S suppliers is divided into main Ca_s and back-up ECa_s capacity. The primary capacity of suppliers is the one that meets the demand under normal circumstances. Supplier's back-up capacity is used only in cases where a disruption occurs in the leading suppliers. Therefore, when the leading supplier is not available, the emergency inventory in the back-up suppliers, will be transferred to the place of demand to provide allocation instead of inaccessible suppliers. Failure to meet the demand in any scenario leads to financial loss and shortages. The place of demand is the construction project site that includes a network of concurrent p projects, each consisting of a set of independent $A(p)$ activities with prerequisite relationships. Each project uses two renewable $R'(p)$ and non-renewable $R(p)$ resources to advance.

Table 1. Summary of the literature review

No	Year	Reference	The approach	The purpose of the study	Number of goals		Disruption	Uncertainty type	Type of costs				Supplier selection	Solving method	Case study
					Single objective	Multi_ objective			Construction supply chain	Transportation	Holding cost	Others			
1	2004	Qi et al. (2004)	Quantitative	↑ Profit	✓		Demand	Demand				Purchasing		Stackelberg game	
2	2005	Hendricks and Singhal (2005)	Quantitative	Investigates effects of supply chain disruptions			✓								
3	2007	Craighead et al. (2007)	Qualitative	↓ Factors of supply chain disruption			✓								
4	2010	Du and Hu (2010)	Quantitative	Design a model to reduce uncertainty	✓				✓					Static chain and net models	
5	2010	Cheng et al. (2010)	Qualitative	Demonstrates the modeling of construction supply chains										The SCOR modeling	The mechanical, electrical and plumbing processes
6	2012	Schmitt and Singh (2012)	Qualitative	Improve resilience			Supply	Demand							Consumer packaged goods (CPG) firm
7	2012	Palliyaguru et al. (2012)	Qualitative	Prevent disaster risks										Questionnaire survey	A water supply in Sri Lank
8	2014	Garcia-Herreros et al. (2014)	Quantitative	↓ Investment cost and expected distribution cost	✓		Facilities			✓	✓			MILP	
9	2015	Snyder et al. (2016)	Qualitative				✓	Supply							
10	2015	Cardoso et al. (2015)	Quantitative	Design and planning of resilient supply chains	✓		✓	Demand		✓	✓			MILP	European supply chain
11	2015	Torabi et al. (2015)	Quantitative	↓ Total cost		✓	✓			✓	✓	Purchasing, contract, fortification	✓	Two-stage stochastic programming model	
12	2015	Behera et al. (2015)	Quantitative	Validating a system of complex construction supply chain management										Qualitative approach of triangulation	A coal-based thermal power plant project
13	2016	Jabbarzadeh et al. (2016)	Quantitative	↓ Total cost	✓		Facilities			✓				Hybrid robust-stochastic optimization	Oil production company
14	2016	Senouci and Mubarak (2016)	Quantitative	↓ Total cost & Time		✓			✓					Genetic algorithm	
15	2017	Kamalahmadi and Parast (2017)	Quantitative	↓ Total cost	✓		Supply & environmental risk	✓		✓	✓	Purchasing, contract, material		Two-stage MIP	
16	2019	Stamatiou et al. (2019)	Quantitative	Prescribe the claims management process										A hybrid top down and bottom up approach	
17	2020	Korpysa et al. (2020)	Quantitative	The impact of entrepreneurial management on company performance											
18	2020	RezaHoseini et al. (2020)	Quantitative	↓ Total cost Project planning and scheduling		✓		Fuzzy-probabilistic	✓	✓		Purchasing		LP	
19	2020	Kaur and Singh (2020)	Quantitative	↓ Total cost		✓									
20	2021	Mehrjerdi and Shafiee (2021)	Quantitative	↓ Total cost, energy consumption, and pollution ↑ Job opportunities		✓	✓			✓		Purchasing		MIP	

End of Table 1

No	Year	Reference	The approach	The purpose of the study	Number of goals		Disruption	Uncertainty type	Type of costs				Supplier selection	Solving method	Case study
					Single objective	Multi_ objective			Construction supply chain	Transportation	Holding cost	Others			
21	2021	Kumar and Sharma (2021)	Quantitative	Provide guidelines for decision making during disruption			Demand							Chaos theory	Oil and gas supply chain
22	2022	Shishodia et al. (2022)	Quantitative	↓ The impact of supplier risks					✓	✓	✓	Purchasing, shortages		Grey relational analysis	
23	2022	Kamalahmadi et al. (2022)	Quantitative	↓ Total cost ↑ Expected service delivery	✓		Supplier and environmental			✓		Purchasing management cost contract, loss cost		Two-stage MIP	
24	2022	Sawik (2022)	Quantitative	Optimization of supply chain operations	✓		Supply, demand and logistics			✓	✓			MIP	
25	2022	Shen andYing (2022)	Quantitative	Create resilience against creeping disruptions	✓		✓		✓					Boundary object theory	A large-scale construction programme Expo 2020 Dubai
26	2023	Ribeiro and Barbosa-Póvoa (2023)	Quantitative	↑Economic and responsiveness objectives		✓	✓				✓	Investment, sales			European SC
27	2023	Tafakkori et al. (2023)	Quantitative	↑ Resilience & cost-efficiency		✓	✓			✓		Purchasing, contract		Robust-stochastic optimization method, back-up supplier	
28	2023	Aldrighetti et al. (2023)	Quantitative	↓ Total cost	✓		✓			✓		Purchasing, contract		Back-up supplier	An international SC in the plastic components industry
29	2023	Aghajani et al. (2023)	Quantitative				Supply			✓	✓	Purchasing, contract, fortification		Two-stage scenario-based stochastic programming model, back-up supplier	The Iranian Red Crescent Society (IRCS)
30	2024	Chen et al. (2024)	Quantitative	↓ Total cost	✓			Demand	✓	✓		Purchasing, penalties	✓	Robust optimization, back-up sourcing	
31	**2024**	**This Paper**	**Quantitative**	**↓ Total cost Project planning and scheduling**	✓		**Supply**	**Scenario based**	✓	✓	✓	**Purchasing, contract**	✓	**MIP**	

For each non-renewable resource, there is a set of suppliers, each of which is assumed to provide only one resource. In addition, each project has a set of renewable resources that can reuse in various activities. Activities using the same renewable resources cannot be performed simultaneously. An activity cannot start unless all of its previous activities completed and its related renewable and non-renewable resources are available. Successful completion of all these projects marks the completion of the construction process.

In the current model, authors specified which of the suppliers should be the leading suppliers and which of the suppliers should be the back-up suppliers to supply the materials needed for the implementation of each project in the construction project site in the event of disruption and emergency. It also specified how much material is transferred from each supplier to the construction project site so that they can minimize the total cost, including ordering, purchasing, shipping, and delay costs. The amount of $a_{s.p}$ (quantity purchased and transported from the leading suppliers to each project), $b_{s.p}$ (quantity purchased and transported from back-up suppliers to each project), as well as $q_{sc.s.p}$ and $pp_{sc.s.p}$ are quantities purchased and transported from primary and back-up suppliers to each project in every scenario to optimize the costs. The project supply chain is shown in Figure 2 with the back-up supplier strategy.

As shown in Figure 2, disruptions risk causes trouble for the project site, defective suppliers marked with a cross. Red dashed lines also mean that it is not possible to buy from the capacity of regular suppliers. Green lines mean the project site problems will be solved with the help of the back-up strategy and the purchase from back-up suppliers' capacity. The main work done in this research shown schematically above.

3.1.1. Problem assumptions

- A collection of primary and back-up suppliers is available for each non-renewable resource.
- Back-up supplier capacity will be used if any of the significant suppliers disrupted.
- Each supplier provides only one resource, and supplier groups specified for each resource.
- The network includes a set of concurrent projects.
- Each project includes a set of activities with prerequisite relationships.
- Projects activities are independent but they face prerequisite constraints on the same project.
- Every project needs a set of non-renewable resources (such as rebar, cement, stone, etc.) and renewable resources (such as machinery, labor, etc.).
- Each project has a set of renewable resources that reused in various activities.
- In each project, activities that use the same renewable resources are not applicable simultaneously.
- An activity cannot start unless all its required renewable and non-renewable resources are available.
- Activities relationships are of FS prerequisite type.
- Under any circumstances, the total demand must be met.
- Project activities are performed without interruption.

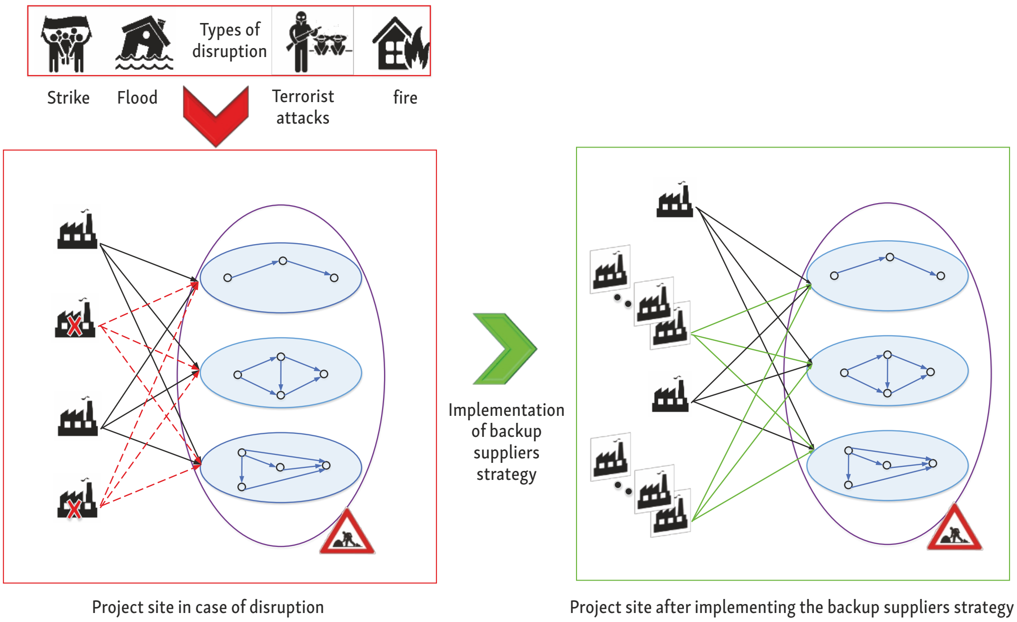

Figure 2. Occurrence of disruption in the construction project supply chain and ways to deal with it

Table 2. Definition of symbols

Sets and Indexes	
P, P'	Set of all projects
$A(p), p \in P$	The set of activities should be performed in project p
$A = \cup_{p \in P'} A(p)$	Set of all activities
$R(p) = \cup_{a \in A'} R(a)$	The set of non-renewable resources required for the activity a
$R = \cup_{a \in A'} R(a)$	Set of all non-renewable resources
$R'(p), p \in P$	Set of renewable resources belonging to the project p

Continue of Table 2

$A'(r') \subset A(p), r' \in R'(p)$	The set of activities in project p that require a renewable source of r
$E(p), p \in P$	The set of prerequisite restrictions for activities in project ($a.b$) ∈ $E(p)$ (for $a.b \in A(p)$) meaning that activity a must be completed before activity b would begin)
$S(r), r \in R(p)$	Set of suppliers for non-renewable source r
$S = \cup_{r \in R'} S(r)$	Set of all suppliers for non-renewable resources

Continue of Table 2

$sc \in SC$	Scenarios
	Parameters
$D_{p.r}$	Non-renewable resource demand *r* for completing all activities in project *p* depending on the source type (amount can be defined in scale of weight, volume, or count)
DD_p	Project *p* due date for completing all activities
Ca_s	Supplier's capacity (defined capacity in the model is the total capacity that the supplier can provide before the date specified in the contract)
ECa_s	Back-up supplier's capacity (defined capacity in the model is the total capacity that the supplier can provide before the date specified in the contract)
d_a	Duration of activity *a* (set day)
t_s^{pre}	Delivery time of the order by the supplier *s*
$t_{s.p}^{tra}$	Shipping time from supplier *s* to project *p* (set day)
C_s^{ord}	Cost of ordering from supplier *s*
C_s^{buy}	Per unit of purchase cost from primary supplier *s*
G_s^{buy}	Per unit of purchase cost from back-up supplier *s*
$C_{s.p}^{tra}$	Shipping cost from supplier *s* to project *p*
C_p^{del}	The delay cost of the project *p*
GG_s	The cost of contracting with back-up suppliers
$Y_{s.s'}$	The dependence of suppliers on each other
$SI_{sc.s}$	Status of supplier *s* in each scenario if supplier *s* is available 1 otherwise 0
π_{sc}	The probability of occurrence for each scenario
M	A big favorite constant
B	Total budget al.ocated to purchase all non-renewable resources
	Decision variables
$X_{s.p}$	The binary variable, if the supplier *s* is used for project *p*, 1 and otherwise 0
$K_{s.p}$	The binary variable, if the back-up supplier *s* is used for project *p*, 1 and otherwise 0
$y_{a.b}, a.b \in A'(r'), a \neq b, r' \in R'(p), p \in P$	The binary variable, if activity *a* is scheduled before activity *b*, 1 and otherwise 0. If *a* and *b* have a common renewable source l in projects *p*.

End of Table 2

$q_{sc.s.p}$	The amount of source sent and purchased from the primary supplier *s* for project *p* in each *sc*
$pp_{sc.s.p}$	The amount of source sent and purchased from the back-up supplier *s* for project *p* in each *sc*
$a_{s.p}$	The amount of source sent and purchased from the primary supplier *s* for project *p*
$b_{s.p}$	Amount of source shipped and purchased from back-up supplier *s* for project *p*
U_{sc}	Loss cost in each *sc*
$ST_a, a \in A$	Start time of activity *a*
$CT_p, p \in P$	Completion time of project *p*
CTT^{total}	Program completion time

3.1.2. Mathematical modeling of the proposed problem

Before presenting the mathematical modeling, the indices, parameters, and variables introduced as described in Table 2.

Mathematical modeling is as follows:

$$\text{Min} F_1 + F_2 + F_3 + F_4 + F_5 + F_6 + F_7 + \sum_{sc \in SC} \pi_{sc}(F_8 + F_9 + F_{10} + F_{11} + F_{12}), \quad (1)$$

$$\begin{cases} F_1 = \sum_{p \in P} \sum_{s \in S(R)} C_s^{ord} X_{s.p} \\ F_2 = \sum_{p \in P} \sum_{s \in S(R)} GG_s K_{s.p} \\ F_3 = \sum_{p \in P} \sum_{s \in S(R)} C_s^{buy} a_{s.p} \\ F_4 = \sum_{p \in P} \sum_{s \in S(R)} C_{s.p}^{tra} a_{s.p} \\ F_5 = \sum_{p \in P} \sum_{s \in S(R)} G_s^{buy} \; b_{s.p} \\ F_6 = \sum_{p \in P} \sum_{s \in S(R)} C_{s.p}^{tra} b_{s.p} \\ F_7 = \sum_{p \in P} CTT^{total} C_p^{del} \\ F_8 = \sum_{p \in P} \sum_{s \in S(R)} C_{s.p}^{buy} q_{sc.s.p} \\ F_9 = \sum_{p \in P} \sum_{s \in S(R)} C_{s.p}^{tra} q_{sc.s.p} \\ F_{10} = \sum_{p \in P} \sum_{s \in S(R)} G_s^{buy} \; PP_{sc.s.p} \\ F_{11} = \sum_{p \in P} \sum_{s \in S(R)} C_{s.p}^{tra} PP_{sc.s.p} \\ F_{12} = MU_{sc} \end{cases}$$

s.t.

$$\sum_{s \in S(r)} a_{s.p} + \sum_{s \in S(r)} b_{s.p} = D_{p.r}, \; p \in P, \; r \in R(p); \quad (2)$$

$$\sum_{p' \in P} a_{s.p} \leq Ca_s X_{s.p}, \quad \forall p \in P, \; r \in R(p), \; s \in S(r); \quad (3)$$

$$q_{sc.s.p} \leq a_{s.p} Si_{sc.s}, \; \forall sc \in SC, \; p \in P, \; r \in R(p), \; s \in S(r); \quad (4)$$

$$q_{sc.s.p} \le Ca_s\left(1-\sum\nolimits_{s'\in S}\left(1-Si_{sc.s'}\right)Y_{s.s'}\right),$$
$$\forall sc \in SC,\ p \in P,\ r \in R(p),\ s \in S(r); \quad (5)$$

$$X_{s.p}+K_{s.p} \le 1,\ \ \forall p \in P,\ r \in R(p),\ s \in S(r); \quad (6)$$

$$\sum\nolimits_{p'\in P} b_{s.p} \le ECa_s K_{s.p},\ \ \forall p \in P,\ r \in R(p),\ s \in S(r); \quad (7)$$

$$PP_{sc.s.p} \le b_{s.p}(1-Si_{sc.s}),$$
$$\forall sc \in SC,\ p \in P,\ r \in R(p),\ s \in S(r); \quad (8)$$

$$PP_{sc.s.p} \le ECa_s\left(1-\sum\nolimits_{s'\in S}\left(1-Si_{sc.s'}\right)Y_{s.s'}\right),$$
$$\forall sc \in SC,\ p \in P,\ r \in R(p),\ s \in S(r); \quad (9)$$

$$\sum\nolimits_{sc} PP_{sc.s.p} \le \sum\nolimits_{sc} a_{s.p}\left(1-Si_{sc.s}\right)+MM\sum\nolimits_{sc}\left(1-Si_{sc.s}\right),$$
$$\forall p \in P,\ r \in R(p),\ s \in S(r); \quad (10)$$

$$\sum\nolimits_{p\in P}\sum\nolimits_{s\in S} C_s^{ord} X_{s.p} + \sum\nolimits_{p\in P}\sum\nolimits_{s\in S(r)} C_s^{buy} a_{s.p} +$$
$$\sum\nolimits_{p\in P}\sum\nolimits_{s\in S(r)} C_{s.p}^{tra} a_{s.p} + \sum\nolimits_{p\in P}\sum\nolimits_{s\in S(r)} G_s^{buy} b_{s.p} +$$
$$\sum\nolimits_{p\in P}\sum\nolimits_{s\in S(r)} C_{s.p}^{tra} b_{s.p} + \sum\nolimits_{p\in P}\sum\nolimits_{s\in S(r)} GG_s K_{s.p} \le B; \quad (11)$$

$$U_{sc} = D_{p.r} - \sum\nolimits_{s\in S(r)}\left(q_{sc.s.p}+PP_{sc.s.p}\right),$$
$$\forall sc \in SC,\ p \in P,\ r \in R(p); \quad (12)$$

$$ST_a \ge \sum_{s\in S}(t_s^{pre}+t_{s.p}^{tra})X_{s.p} + \sum_{s\in S}(t_s^{pre}+t_{s.p}^{tra})K_{s.p},$$
$$\forall a \in A(p),\ p \in P,\ r \in R(a); \quad (13)$$

$$ST_a + d_a \le ST_b,\ \ \forall (a, b) \in E(p),\ p \in P; \quad (14)$$

$$CT_p \ge ST_a + d_a,\ \ \forall a \in A(p),\ p \in P; \quad (15)$$

$$ST_a + d_a - M(1-y_{a,b}) \le ST_b,$$
$$\forall (a, b) \in A'(r'),\ a \ne b,\ r \in R'(p'),\ p \in P; \quad (16)$$

$$ST_b + d_b - M(y_{a,b}) \le ST_a,$$
$$\forall (a, b) \in A'(r'),\ a \ne b,\ r \in R'(p'),\ p \in P; \quad (17)$$

$$CTT^{total} \ge CT_p,\ \ \forall p \in P; \quad (18)$$

$$X_{s.p}, y_{a,b}, K_{s.p} \in \left(0,1\right); \quad (19)$$

$$q_{sc.s.p},\ ST_a, CT_p, CTT^{total},\ PP_{sc.s.p}\ .a_{s.p}\ , b_{s.p}, U_{sc} \ge 0. \quad (20)$$

Constraint 1, the objective function of the model, indicates that its goal is to minimize the cost of all projects, which is equal to the sum of the costs of purchasing, ordering, shipping from primary and back-up suppliers to the project site, cost of contracting with the back-up suppliers and the delay cost of the projects. Constraint 2: total orders amount for each project from each primary and back-up supplier should equal the demand for each project. Constraint 3: the amount of primary supplier orders is at most equal to the capacity of that supplier. Constraint 4 limits the amount of shipped and purchased source from each leading supplier to its availability in each scenario. Constraint 5 indicates the dependence of suppliers on each other and the reduction of primary suppliers' initial production in case of disruption in other suppliers. Constraint 6 shows that each supplier used as the leading supplier or back-up supplier. Constraint 7 limits the allocation of emergency inventory in back-up supplier to their emergency capacity. Constraint 8 limits the amount of sent and purchased resources from each back-up supplier to availability in any scenario. Constraint 9 indicates the dependence of suppliers on each other and the reduction of back-up suppliers' initial production in case of disruption in other suppliers. Constraint 10 eliminates the use of emergency inventory in the absence of disruption and it ensures that the amount allocated as emergency inventory does not exceed the amount to be delivered by the defective suppliers in case of availability. Constraint 11 shows that the total cost of ordering, purchasing, shipping from the primary and back-up suppliers, and the cost of contracting with the back-up supplier must be less than the intended budget. Note that all concurrent projects have a single budget. Constraint 12 calculates the dissatisfied cases and unsatisfied demand in each scenario. Constraint 13 indicates that an activity can begin when the supplier has ensured the supply of the resource along with on-time delivery of products. In other words, an activity can start after all the non-renewable resources needed are available. Constraint 14 shows the prerequisites for the activities. Constraint 15 indicates the completion time of the project. Constraint 16 and 17 indicate the prerequisite and post-requisite of two activities that share a common renewable source. In other words, activities that use the same renewable resources cannot start simultaneously. Constraint 18 indicates the finishing time of the entire chain.

4. Analysis and numerical results

4.1. Experimental problem design and data production

Numerical examples of this research benefited from random data created based on uniform distribution function, and based on these data results, sensitivity analysis performed. Here are some independent and simultaneous projects for which this article tries to select a supplier who will provide the materials needed for the project site in the shortest possible time. On the other hand, the shorter the project time, the lower the supply chain costs. Depending on the different disruption scenarios, this process may be problematic and for this reason, back-up suppliers are also used to facilitate the process of projects. The construction supply chain's operation shown in the figure below at the time of occurrence of a disorder and use of a back-up supplier strategy.

According to Figure 3, a contractor has three simultaneous projects each including three activities. Activities should perform according to the prerequisite relationships. In the third project, activities 8 and 9 have a common renewable resource. Each project requires two non-renewable sources 1 and 2. Three suppliers with a certain capacity level, purchase cost, and particular ordering cost provide the first source (concrete). 2 – other suppliers also provide the second source (steel) with a certain capacity level, purchase cost, and particular ordering cost. This project site may disrupt for reasons such as natural disasters. In these cases, the same leading suppliers who also have back-up capacity would take action. Action will be in this way: three back-up suppliers having certain capacity level, purchase cost and ordering cost, supply concrete; two other back-up suppliers having certain capacity level, purchase cost and particular ordering cost, supply steel.

Each primary and back-up supplier has its own production capacity, production time, and costs. Each supplier has two different purchase prices for their products: one for normal conditions and the other for disturbed conditions, that is, conditions in which the supplier used as a back-up supplier. It assumed that the purchase price during disruption is higher than the purchase price under normal circumstances. The contract with the back-up supplier also has a fixed cost called the concluding contract cost. After selecting a back-up supplier, it produces some of the material allocated to it as an emergency inventory and keeps it in its warehouse. Each back-up supplier has limited capacity to maintain this emergency inventory. Information related to primary and back-up suppliers given in Tables 3 and 4.

In Table 5, by defining parameter $Y_{s.s'}$, which represents a decimal fraction of the supplier's capacity as a result of the supplier disruption, suppliers' mutual dependency in all three defined scenarios reflected with equal probabilities (0.33). $Y_{s.s'}=1$ means a malfunction in the supplier s results in a 100% reduction in the capacity of the supplier s'. The table of this parameter shows how the material capacity of other suppliers to serve the projects is limited in case of disruption in each supplier. In this research, it assumed that some suppliers located in the environment close to each other, and the supplier S disruption leads to a percentage reduction of the capacity of the supplier s.

According to Table 6, each of our projects requires resources of the first and second commodity types to complete. This table also shows the cost of delay and the appointed time to start each project.

According to Table 7, each product has a specific shipping time and cost for shipping from suppliers to each project.

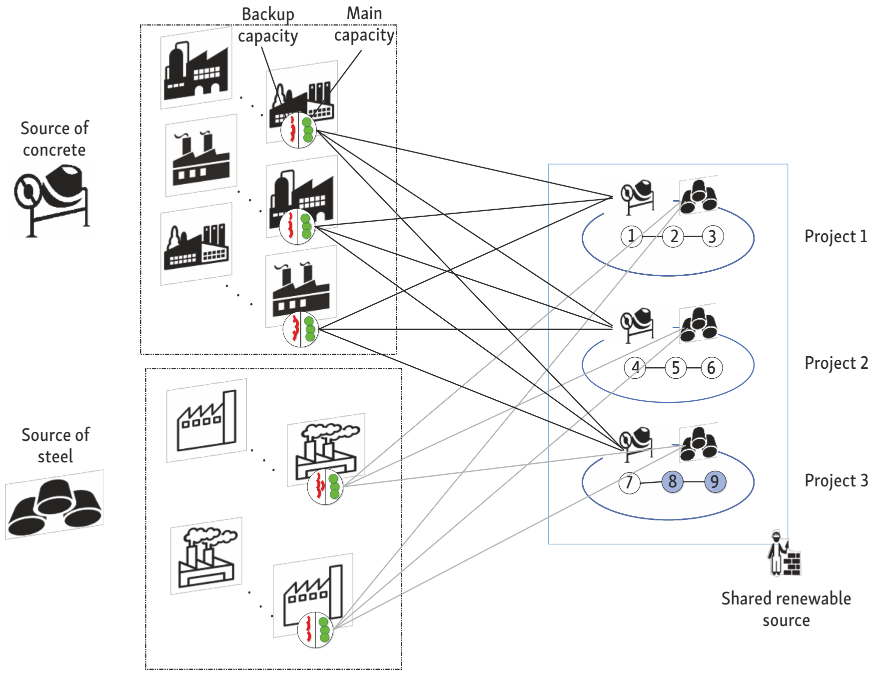

Figure 3. Coordinated network of back-up supplier selection and project scheduling, activity scheduling and their sequence

Table 3. Parameters related to the primary suppliers

Suppliers	Production capacity	Production time (day)	Ordering cost	Purchase cost
S_1	95	14	22	5
S_2	100	11	20	6
S_3	90	10	20	7
S_4	135	15	20	7
S_5	120	12	22	8

Table 4. Parameters related to back-up suppliers

Suppliers	Production capacity	Production time (day)	Ordering cost	Purchase cost	Concluding a contract cost
S_1	60	14	22	37	100
S_2	45	11	20	36	100
S_3	50	10	20	35	100
S_4	45	15	20	37	100
S_5	40	12	22	38	100

Table 5. Dependence of suppliers on each other

Suppliers	s'_1	s'_2	s'_3	s'_4	s'_5
S_1	0	0.5	0.3	0.1	0
S_2	0.2	0	0.2	0	0
S_3	0.1	0.2	0	0.1	0.1
S_4	0	0.2	0.3	0	0
S_5	0	0	0.2	0	0

Table 6. Parameters related to projects

Project	Appointed time	Delay cost	Type 1 Commodity Demand	Type 2 Commodity Demand
P_1	0	3	50	40
P_2	0	2	35	50
P_3	0	4	45	45

Table 7. Parameters related to the transportation of resources from suppliers to each project

Suppliers	Average shipping time			Shipping cost		
	P_1	P_2	P_3	P_1	P_2	P_3
S_1	2	2	1	5	5	5
S_2	6	2	6	6	6	6
S_3	6	6	4	7	7	7
S_4	4	2	4	8	8	8
S_5	5	6	5	9	9	9

4.2. Analysis of results

GAMS software and Cplex solver used to solve the model, on a computer with CPU Intel Core i7, 2.53 GHz, and 8 GB of RAM. In this section, the selection of the primary and back-up suppliers and costs resulting from the mathematical model will state first. Then, the next section will deal with project scheduling.

4.2.1. Analysis of suppliers' selection results in each scenario

Due to the scenario-oriented nature of our model, three separate scenarios with equal probability of occurrence defined. In the general model, uncertainty investigated using a set of discrete scenarios having the same probability of occurrence. We define *Sc* scenarios for different types of events that may occur due to the disruption. Note that by using the terms "disrupted" and "inaccessible", we indicate the lack of access to a supplier due to a disruption. We assign the parameter $Si_{sc.s}$ as the supplier *S* status in the *Sc* scenario. If a supplier is available, the parameter will equal one, if it is not available then the parameter will be zero. The first and fifth suppliers are available almost 70% of the time. The fourth supplier is available in all scenarios. The availability of suppliers means that they are not disrupted. Second and third suppliers are available only about 30% of the time. In this model, we also specify scenario-dependent variables such as the amount of material purchased from each primary and back-up supplier in each scenario. All three scenarios highlighted in different gray shades. Also, in Tables 8 and 9, the amount of material purchased from each primary supplier can be identified by green color, and the amount of material purchased from each back-up supplier identified by red color. In case of any problem or delay of any project, we require to pay a penalty in each scenario, the amount of which specified in Table 10.

Table 8. Amount of original purchased materials in each scenario

The selected primary suppliers in each scenario	Project 1	Project 2	Project 3
*Sc*1.*s*1	✓ 35	✓ 30	✓ 30
*Sc*1.*s*2		✓ 5	✓ 5
*Sc*2.*s*4	✓ 40	✓ 50	✓ 45
*Sc*2.*s*1	✓ 5	✓ 15	✓ 10
*Sc*2.*s*1	✓ 35	✓ 20	✓ 30
*Sc*3.*s*4	✓ 25	✓ 35	✓ 30

Table 9. Amount of purchased back-up materials in each scenario

Selected back-up suppliers in each scenario	Project 1	Project 2	Project 3
*Sc*1.*s*3	✓ 15		✓ 10
*Sc*2.*s*3	✓ 15		✓ 10

Table 10. The amount of deficiency in each scenario

The amount of deficiency in each scenario	Scenario 1	Scenario 2	Scenario 3
U_{sc}	0	35	15

4.2.2. Analysis of results related to the selection of final suppliers

The primary suppliers selected for each project listed in Table 11.

Table 11. Selection of primary suppliers

Suppliers	P_1	P_2	P_3
S_1	✓ 35	✓ 30	✓ 30
S_2		✓ 5	✓ 5
S_4	✓ 40	✓ 50	✓ 45

As mentioned in the previous section, the first and fifth suppliers are available almost 70% of the time. The fourth supplier is available in all scenarios. Second and third suppliers are available only about 30% of the time. In other words, the first and fifth suppliers are disturbed about 30% of the time, and the second and third suppliers are disturbed about 70% of the time. Also, the fourth supplier is not disrupted in any scenario. According to this info, the most reliable supplier for concrete is Supplier 1, which supplies all three projects to its total capacity, despite the higher ordering cost. This result also affected by shipping cost, and shipping time. As the parameters show us, shipping cost from supplier one to the first to third projects is lower than others. On the other hand, due to the cost of delay in the objective function and efforts to reduce it, delivery time also plays a vital role in choosing the right supplier. Therefore, another reason for choosing Supplier 1 for the first to third projects is less delivery time than other suppliers. Due to the lower purchase price of Supplier 2 compared to Supplier 3, the continuation of the first source demand is met by Supplier 2. Suppliers 4 and 5 are for supplying steel sources. Supplier 4 is available in all scenarios and has lower purchase, shipping, and ordering prices than Supplier 5. That is why this supplier met steel demand. All these values shown in Table 11.

Table 12. Selection of back-up suppliers

Suppliers	P_1	P_2	P_3
S_3	✓ 15		✓ 10

As shown in Table 12, given that in our model for each project, only one of the primary or back-up capacities of each supplier can be used; here, supplier three is used for the first and third projects, because the purchase price of this back-up supplier is lower than back-up suppliers 1 and 2. Also, due to high cost of back-up suppliers, there is more delicacy and precision in selecting these suppliers.

The value of the cost function in this research is equal to Z = 172894.85. Our objective function consists of two parts: principal components and scenario-based. All components of these two parts play an essential role in the total value and in the intellectual orientation changes of the senior managers to provide the different costs required by the objective function. The central part of the objective function includes ordering cost of the primary suppliers, the cost of purchasing, and shipping from the primary and back-up suppliers, the cost of concluding a contract with the back-up suppliers, and the delay in project costs. The scenario-based part includes the costs of purchasing and transporting from primary and back-up suppliers and the cost of shortages in each scenario. Cost of shortages is demand amount not met in every scenario and requires us to pay penalty. The main costs shown in Figure 4.

Concerning cost components, we show the share of each component and their impact on the supply chain in Figure 4. As can be seen, the highest costs share of the central part include the costs of transportation and purchases from the primary suppliers. The reason is that the cost per unit of purchase from the primary suppliers is meager, and that is why our model buys more goods from the primary suppliers. As a result, the share of the total cost of shipping and purchasing costs from major suppliers increases. Cost of purchasing from back-up suppliers is in the next rank because the cost of per unit purchased from back-up suppliers is very high despite the small number of purchased and shipped back-up goods. Because these suppliers work in disruptive and necessary conditions, it is expected that they have a high price. Due to the small number of goods purchased from back-up suppliers and the equal cost of shipping goods from both the primary and back-up suppliers, the lowest share of the central part costs includes shipping costs from back-up suppliers.

The costs of each scenario, except for the shortage' costs, shown in Figure 5. Since in scenarios 1 and 3 fewer primary suppliers disrupted, the costs of purchase and

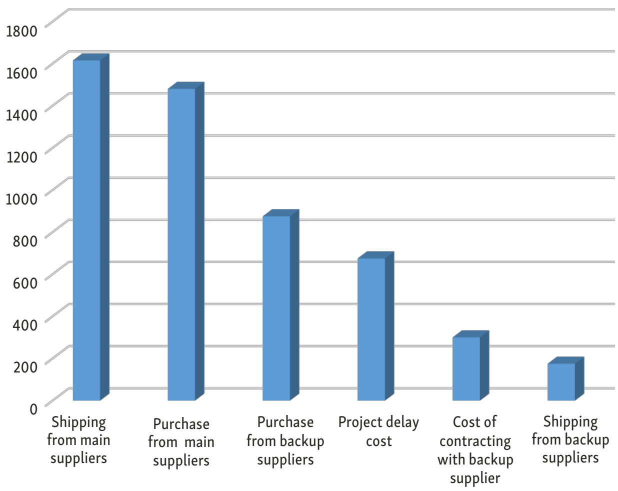

Figure 4. Main costs share of the supply chain

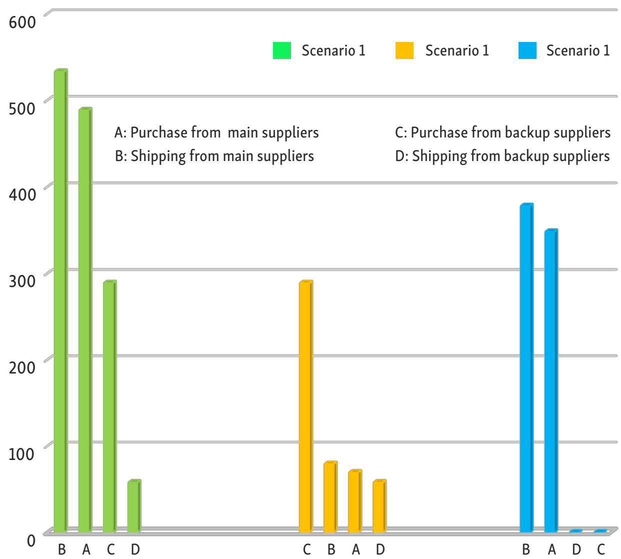

Figure 5. Scenario-driven costs share of the supply chain

shipping from primary suppliers are higher in these two scenarios. Nevertheless, in scenario two, there are only two suppliers as steel source, so we have to buy from back-up suppliers for the first source which costs more. In scenario 3, the total demand is met with the primary suppliers and the back-up costs reduced to zero.

In Figure 6, the amount of shortage in each scenario shown. Shortage cost in each scenario has the highest share of supply chain costs due to very high penalty costs; this cost ensures that the minimum amount of shortage occurs. Due to its higher costs, the authors examined it separately.

Based on the Gantt chart, the schedule of 9 activities of all three projects shown in Figure 7. In Figure 7, Project 1 shown in blue, Project 2 in orange, and Project 3 in green. As can be seen, due to the unavailability of suppliers and the time of transportation and preparation of materials to the project site, the first starting time of Project 1 is in time 49, and this project lasted until time 74. To show the preparation and shipping times in a better way, Project 1 has been selected as desired. Using limitation 12 and Tables 2 and 6, the start time of the first activity for concrete is 49 and 19 for steel. We will use the maximum time obtained for the start time of each activity, so the final start time of our first activity will be 49. Materials required for projects 2 and 3 arrived at the site in less time than project one, so project two was completed earlier than other projects. Project three involves two activities sharing a common renewable resource, and took more time. Due to delay costs and the unavailability of some resources, the entire project chain completed in time 75.

4.3. Sensitivity analysis

In this section, with several separate case studies, by performing sensitivity analysis, we examined different answers to clearly show the model behavior, reliability, and flexibility.

4.3.1. Case Study # 1

To demonstrate the efficiency of the construction project supply chain model without disruption scenarios in this section, we examine the different answers with a scenario to fully determine how the project site's required materials met if all suppliers are available. If all suppliers are available and can use their full capacity, for the first type of material supplier 1 for the first and third projects, supplier 2 for the second project used. This is because of cheaper purchasing cost of Suppliers 1 and 2 comparing Supplier 3. A larger amount of materials purchased from supplier 1due to the higher ordering cost of Supplier 1 comparing to Supplier 2; this indicates that purchase cost is more important than ordering cost in resource allocation. Supplier 4 type used for the first to third projects for material number 2. The model is shown fully in Figure 8.

4.3.2. Case Study # 2

In the main solution of the model with different scenarios, the disruption of each scenario occurred by equal probability of occurrence. Also, each supplier had a specific capacity to compensate for material shortages with another supplier in the event of a disruption or lack of capacity. In the current single scenario, all suppliers are available, but majority of them have less capacity than before, and the issue of coordination and resource management are doubly essential. According to Figure 9, for the second and third projects, the total supply capacity of supplier one is used and for the first project, the total supply capacity of supplier two used. Supplier 3 has several materials to supply concrete, because of limitation 6, which states that the model requires a supplier to be selected either as a back-up or primary, the model uses the back-up capacity of Supplier 3 for all three projects and provides the first type of material. To supply the second type of material, as before Supplier 4 used, which is the most suitable supplier in terms of costs, for the first to third projects.

4.3.3. Case Study # 3

In the previous case study, it was investigated that limitation six may have increased supply chain vulnerabilities. In order to inform the project beneficiaries to improve the performance in the construction supply chain, the model examined without limitation six. If it is possible to use one supplier as both the main and back-up supplier to meet

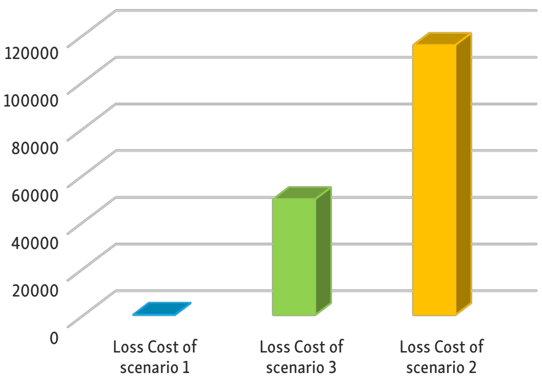

Figure 6. Shortage costs share in each supply chain scenario

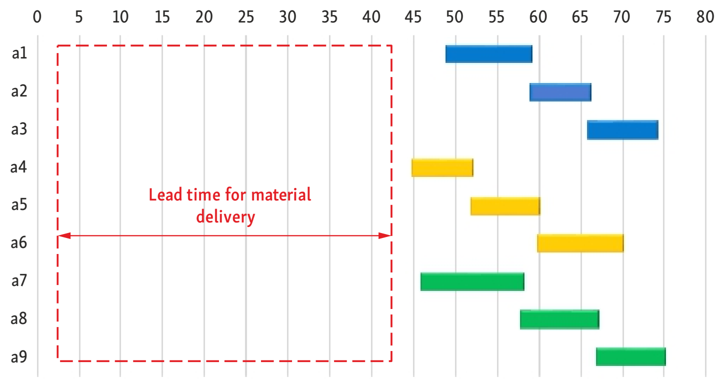

Figure 7. Gantt chart, project supply chain's schedule of activities

the demand of the project site at the same time, according to Figure 10, for the first source of the first, second and third projects Supplier 1, and the first and third projects Supplier 2, and finally the low capacity of Supplier 3 used for the third project. For the second source, it works the same as the previous model. A tangible and noteworthy point in this regard is that our model has chosen Supplier 3 for the first source among all three back-up suppliers because of the cheaper purchase cost and not because of its low core capacity, because in the previous model, due to the low capacity of Supplier 3, this supplier was assumed to be inaccessible. Total costs significantly reduced due to the total consumption of the primary suppliers' capacity and less usage of expensive back-up suppliers.

5. Discussion and managerial insights

In this research, to improve the ability of the supply chain to deal with unexpected risks and disruptions, the element of flexibility, i.e., the strategy of the back-up supplier is included in the appropriate supplier selection for supplying construction projects' materials. This research model

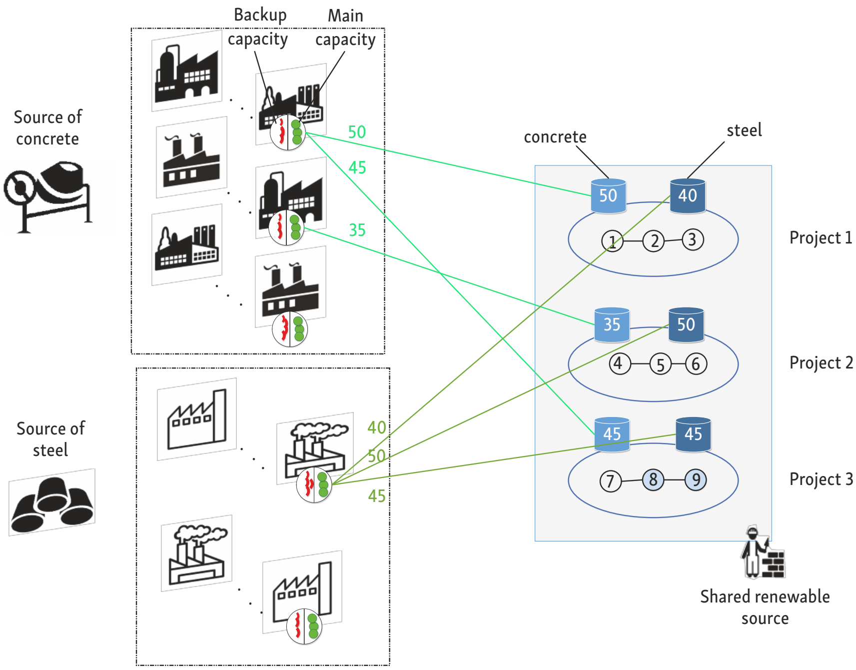

Figure 8. Coordinated network of main and back-up supplier selection

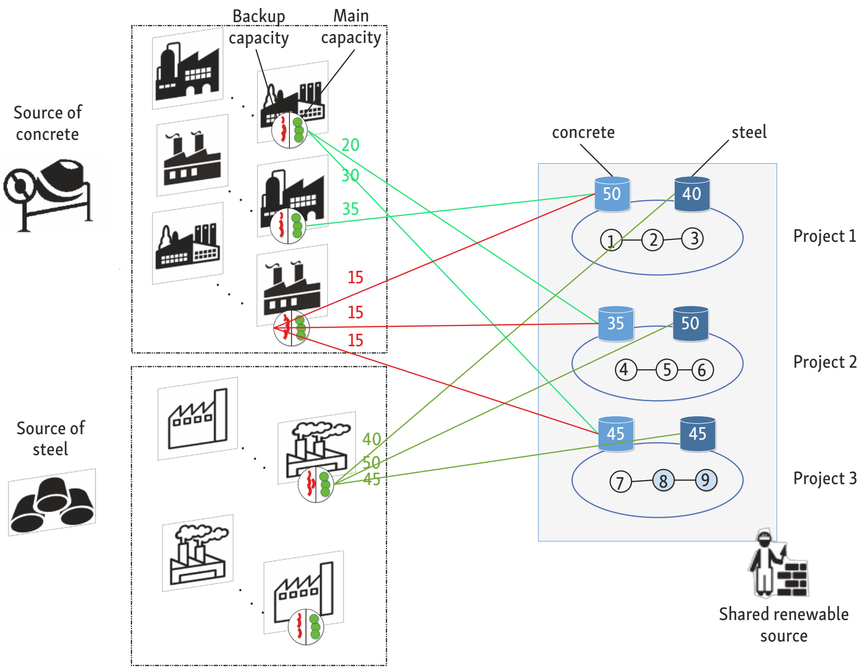

Figure 9. Coordinated network of main and back-up supplier selection

provides significant insights into proper risk management for operations and supply chain managers. Adding strategies such as using a back-up supplier to the project's supply chain requires managers to invest in disruption mitigation programs before any disruption occurs. Given the low probability of disruptions, managers may be reluctant to value such investments. Applying this strategy may not be cost-effective due to the low probability of unexpected disruptions. However, failure to consider possible cases can lead to selecting an incorrect set of suppliers. Regardless of disruptions, the supplier with the highest probability of unavailability selected as the primary supplier, and many orders allocated to it. In this case, if any accident occurs, in addition to the higher cost, more projects will face problems, in which case the fine we are required to pay is much higher than the cost of prevention.

The results of the model and different scenarios show the effectiveness of this strategy for improving the responsiveness of suppliers to provide resources for projects. In the sensitivity analysis of this research, the authors carefully examined that if the capacity of suppliers decreases, how the purchase cost factor, order cost and shipping cost become more critical in choosing the appropriate supplier. It is also shown that in case of necessity or lack of necessity, to choose a supplier either as a back-up supplier or as a primary supplier, the amount allocated from each supplier to each project makes a difference. The results show that operations and supply chain managers may need to work with suppliers during a disruption. In addition, by using a parameter, the mutual effect of suppliers, in the same environment on each other's capacity in disturbance time clearly shown. It is shown so that the importance of the environmental risk compared to other supply chain risks can also be determined. The proposed model can be used as a decision-making tool to help experienced supply chain managers evaluate and make appropriate decisions about supplier alternatives in the event of disruption. It also contributes to their ability to ensure continuity of resource provision against disruptions caused by disasters. The findings show that selection process of the appropriate supplier in this article helps construction project managers to actively select reliable suppliers to reduce supplier risk and the disruptions' influence in the event of a disaster. The proposed model is a unique one which helps supply chain managers optimally design their order allocation policies from multiple sources to meet demands while keeping overall cost and risk at the lowest possible level.

6. Conclusions and future directions

Choosing a highly reliable supplier is very important, especially in the construction industry. The construction industry is a project production industry that operates in an environment of considerable uncertainty and complexity and this feature distinguishes it from other industries (Fearne & Fowler, 2006). Many articles written in this field over the years, often primarily qualitative and with managerial approaches. For this reason, lack of mathematical models under this subject is felt. In addition, the establishment of resilient supply bases for supply chains in response to uncertainty caused by a variety of disruptions is another significant issue. Disruption in the construction supply chain can have significant economic effects. Resilience, therefore – as a concept that maintains the capacity of a system to adapt to changes and to deal with surprises while maintaining the basic function and structure of the system (Holling, 1973) – has emerged as an important tool for risk management (Ponomarov & Holcomb, 2009).

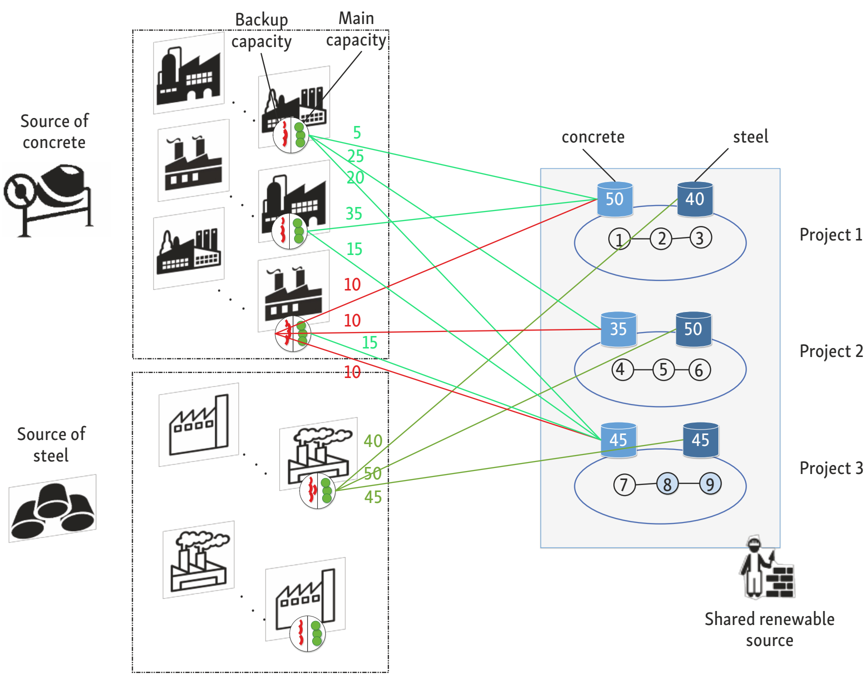

Figure 10. Coordinated network of main and back-up supplier selection

In today's world, supply chain disruption risk management has become vital part of supply chain management strategy (Stecke & Kumar, 2009). It is because disruptions are unpredictable reality in today's complex world that planning to deal with them before happening is far more cost-effective than taking action after a disruption has occurred.

This paper presents a numerical model of mixed-integer programming for selecting and allocating supplier demand intending to minimize total costs, including logistics costs, delay costs, and scenario-based costs. The effect of adding a back-up supplier strategy to the construction project supply chain also investigated. This study, in addition to scheduling projects, has also considered the impact of the back-up supplier strategy on the selecting resilient suppliers. Then, to validate the model, an example is presented and the results of the proposed model discussed under various conditions.

The findings and achievements of this research can be summarized as follows:

- Providing a new model for supply chain planning (project planning and resource supply);
- Making a project supply chain model resilient using the back-up supplier strategy;
- Scheduling project activities and avoiding delays;
- Observance of project time constraints and scheduling of project activities accordingly;
- Increasing system flexibility by considering possible scenarios.

This study demonstrated how adding a back-up supplier strategy to the supply chain can create opportunities to minimize the impact of disruptions and reduce supply chain costs. This study can be used to reduce the destructive effects of disruptions in construction companies where several projects managed simultaneously.

For future studies, the authors suggest that the model be planned periodically to examine the possibility of adopting inventory purchasing and maintenance strategies in different periods. Furthermore, in the present study, if the capacity of a regular supplier disrupted, according to the database, the capacity of another back-up supplier would be used. In this study, the mentioned model does not specify precisely from which back-up supplier the required materials should be purchased. This issue can also be considered in future studies in the form that back-up suppliers also have a list of choices, so a priority list of back-up suppliers can be prepared and presented to the decision maker. This study is the first of its kind, so some of the certain limitations identified and should be acknowledged. Our model could capture almost all different scenarios that might happen as a result of supplier and supply chain disruptions, but parameters deterministic values may not able to fully cover the supply chain's dynamic nature and this needs more attention. Moreover, the authors did not have the opportunity of using data from multiple firms to validate the findings of this study. Furthermore, researchers could not consider a time horizon in their back-up strategy and the model assumed to be performed in a one-cycle demand period.

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